Input-Output Analysis (Subject editor: Sangwon Suh)

A Risk-Based Approach to Health Impact Assessment for Input-Output Analysis
Part 2: Case Study of Insulation*

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DOI: http://dx.doi.org/10.1065/lca2004.10.186.2

Abstract

Goal, Scope and Background. In the first part of this paper, we developed a methodology to incorporate exposure and risk concepts into life cycle impact assessment (LCIA). We argued that both risk assessment and LCIA are needed to consider the impacts of increasing insulation for single-family homes in the US from current practice to the levels recommended by the 2000 International Energy Conservation Codes. In this analysis, we apply our model to the insulation case study and evaluate the benefits and costs of increased insulation for new housing.

Results and Discussion. The central estimate of impacts from the complete insulation manufacturing supply chain is approximately 20 premature deaths, 500 asthma attacks, and 8,000 restricted activity days nationwide for one year of increased fiberglass output. Of the health impacts associated with increased insulation manufacturing, 83% are attributable to the supply chain emissions from the mineral wool industry, which is mostly associated with the direct primary $PM_{2.5}$ emissions from the industry (98%). Reduced energy consumption leads to 1.2 premature deaths, 30 asthma attacks, and 600 restricted activity days avoided per year, indicating a public health 'payback period' on the order of 14 years. About 90% of these benefits were associated with direct emissions from power plants and residential combustion sources. In total, the net present value of economic benefits over a 50-year period for a single-year cohort of new homes is $100 million with a 5% discount rate, with 40 fewer premature deaths in this period.

Conclusion, Recommendation and Outlook. We have developed and applied a risk-based model to quantify the public health costs and benefits of increased insulation in new single-family homes in the US, demonstrating positive net economic and public health benefits within the lifetimes of the homes. More broadly, we demonstrated that it is feasible to incorporate exposure and risk concepts into I-O LCA, relying on regression-based intake fractions followed by more refined dispersion modeling. The refinement step is recommended especially if primary $PM_{2.5}$ is an important source of exposure and if stack heights are relatively low. Where secondary $PM_{2.5}$ is more important, use of regression-based intake fractions would be sufficient for a reasonable risk approximation. Uncertainties in our risk-based model should be carefully considered; nevertheless, our study can help decision-makers evaluate the costs and benefits of demand-side management policy options from a combined public health and life cycle perspective.

Keywords: Air pollution; cost-benefit analysis; fiberglass insulation; input-output analysis; intake fraction; life cycle impact assessment; public health; risk analysis

* Part 1: Methodology
(DOI: http://dx.doi.org/10.1065/lca2004.10.186.1)

Introduction

Home heating and cooling energy consumption is reduced by insulating building envelopes. Today, insulation is part of every new home built in the United States. However, the current practice is not meeting the levels of insulation recommended by the International Energy Conservation Code (2000). Increasing insulation in new homes not only has the potential to benefit residents with reduced energy bills, but can also reduce environmental burdens by decreasing air pollution from power plants and heating systems. However, increased manufacturing of insulation has its own environmental burdens, necessitating a thorough analysis to inform public policy.

In the first part of this paper <http://dx.doi.org/10.1065/lca2004.10.186.1>, we proposed an analytical framework that could be applicable to this case. In our model, we calculate the influence of increased insulation manufacturing on direct and upstream economic outputs of insulation and fuel sources, using an input-output approach. We quantify incremental emissions of $PM_{2.5}$, NO_x and SO_2 as particulate matter precursors, and selected air toxics, using a pollution intensity matrix. We estimate population exposures using an intake fraction approach that accounts for variations in exposure as a function of region and stack height, with additional dispersion modeling conducted for a subset of sources that contribute significantly to total population risks. We quantify health impacts using concentration-response functions for morbidity and mortality and assign monetary values to health outcomes to facilitate comparisons with the economic savings associated with insulation.

1 Results

In this section, we present the deterministic findings of all the components of our analysis, using central estimates for all uncertain parameters. We address the overall uncertainties in the Discussion section.

1.1 Total output estimation

The current insulation in an average home built today has an R-value (i.e., the thermal resistance in ft² °Fh/Btu) of about 16, while the recommended IECC standard is an R-value of 20. Meeting the IECC 2000 code with fiberglass insulation would require about 260 kg of additional insulation per unit. Since about 1.2 million single-family homes are built each year, the total potential increase in insulation consumption is 330 thousand metric tons per year or 10% of the current production level [1–4].

In monetary terms, the total value of shipment for the mineral wool industry was $4.4 billion in 1997 [5]. This value includes both fiberglass and non-fiberglass manufacturers and needs to be corrected only to include the value for fiberglass manufacturers. However, information such as price of fiberglass insulation at the plant-level is proprietary, so we have developed a model to estimate the value of shipment for fiberglass manufacturers as a function of the number of employees. Based on the central estimate of employment at non-fiberglass manufacturers as well as an assumption that the number of employees is a reasonable proxy for the economic output at each plant, the output for the fiberglass/mineral wool manufacturers was estimated to be $3.3 billion. Using this revised value of shipment, we estimate a final value of $406 million as the incremental final demand at producer's price for fiberglass/mineral wool (90% CI: $387 million, $424 million). This would correspond to $540 million at consumer's price after including cost of installation according to RSMeans [6].

For the incremental dollar value of the fuel savings, we first calculated the demand reduction in consumer's price based on the total energy savings from our previous analysis [7], and estimated the economic value at the producer's price given reported unit prices [8–12]. Consequently, the estimated annual fuel cost savings for natural gas, fuel oil and electricity are $24 million, $1 million, and $9 million, respectively.

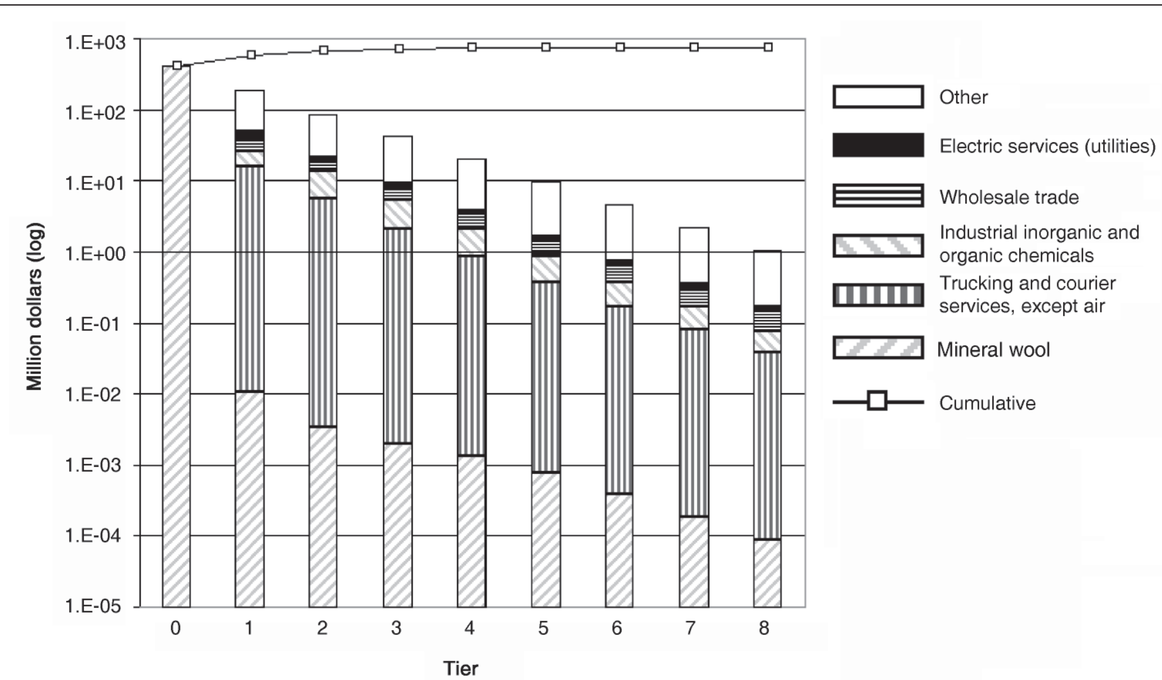
1.2 Direct + upstream economic input and output

The total increase in economic output for the direct and indirect supply chain activities for increased fiberglass insulation production is $755 million, which is about twice as much as the final demand for insulation alone. This reflects the fact that the increased demand for insulation triggers insulation manufacturers to buy goods and services to meet the production level demanded. Direct suppliers to the insulation manufacturers, in turn, demand goods and services from their own direct suppliers, and this 'ripple' effect continues throughout the economy, with the marginal impacts asymptotically approaching zero for the higher tier sectors. **Fig. 1** shows the tierwise and cumulative economic outputs for the mineral wool industry. The direct suppliers to the insulation manufacturers in tier 1 include 'trucking and courier services (except air)', 'electric services', 'wholesale trade', 'industrial inorganic and organic chemicals', and others, with direct suppliers alone exceeding 350 sectors. Note that service industries such as trucking and courier services and wholesale trade are not usually included in the conventional process-based LCA approach.

For the energy savings, the direct and indirect supply chain activities represent demand reductions that ripple throughout the economy. The total decrease in economic output associated with direct and indirect fuel production activities is $70 million per year, nearly double the value of the end-use energy savings in tier 0 (**Fig. 2**). Of the $70 million, 70% of the total comes from 'natural gas transportation and distribution' (37%), 'electric services' (14%), 'crude petroleum and natural gas' (14%), and 'other repair and maintenance construction' (6%).

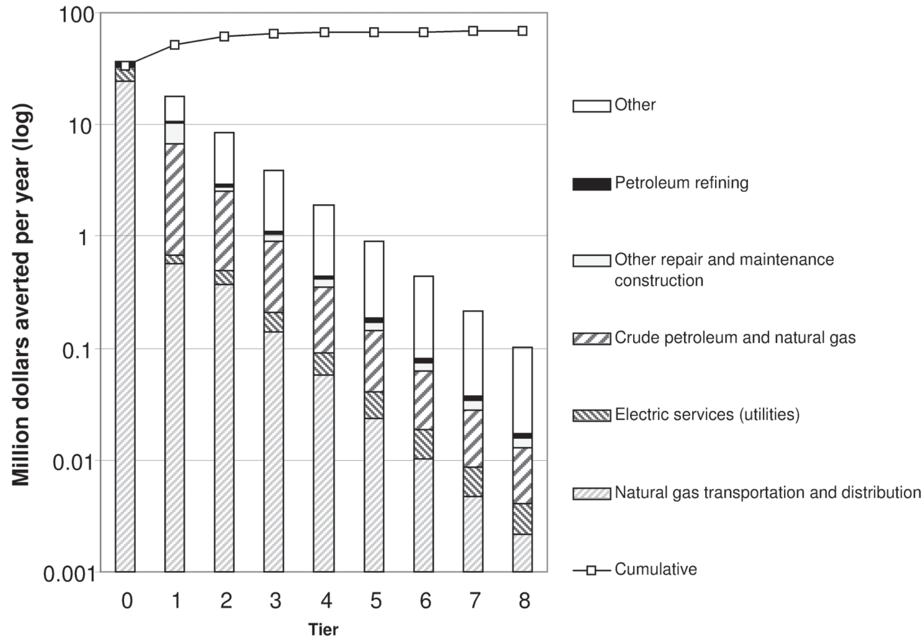
1.3 Supply chain emissions

Total I-O analysis emissions are based on economic output and emission intensities, which are commonly expressed in tons of pollutant emitted per dollar of sales at producer's price. The emission intensities for fiberglass/mineral wool,



Note: 'Other' includes 'Miscellaneous plastics products, n.e.c.', 'Plastics materials and resins', 'Glass and glass products, except containers', 'Natural gas distribution', 'Paper and paperboard mills' and over 450 other industries.

Fig. 1: Tierwise supply chain economic outputs associated with increased insulation production



Note: 'Other' includes 'Computer and data processing services; including own account software', 'Wholesale trade', 'Accounting, auditing and bookkeeping, and miscellaneous services, n.e.c.', 'Real estate agents, managers, operators, and lessors', 'Engineering, architectural, and surveying services' and over 450 other industries.

Fig. 2: Tierwise supply chain economic outputs associated with reduced energy production

Table 1: Emission intensities for mineral wool and fuel source industries (tons per million dollars), with percentile ranking across BEA industries

	Mineral Wool	Electricity	Natural Gas	Fuel Oil
$PM_{2.5}$	1.13 (4th)	0.72 (7th)	0.03 (69th)	0.24 (60th)
No_x	1.33 (7th)	31.85 (1st)	6.66 (57th)	2.61 (75th)
SO_2	0.86 (10th)	67.78 (1st)	0.07 (80th)	4.20 (69th)

electricity, natural gas and fuel oil are listed in **Table 1**, along with their ranking in percentile across all BEA industries. These Fig.s demonstrate that, while the mineral wool industry is relatively emissions-intensive (for $PM_{2.5}$, NO_x and SO_2, in the 4th, 7th, and 10th percentile across all BEA industries, respectively), electricity is substantially more emissions-intensive for NO_x and SO_2.

Applying these emission factors, the total supply chain emissions associated with an increased demand for fiberglass insulation are 480 tonnes of $PM_{2.5}$, 1200 tonnes of NOx and 1500 tonnes of SO_2. The mineral wool industry accounts for 87% of the total $PM_{2.5}$ supply chain emissions (**Fig. 3**), largely due to direct (tier 0) emissions. For NO_x and SO_2, electric services and the mineral wool sector together account for more than 80% of the total supply chain emissions.

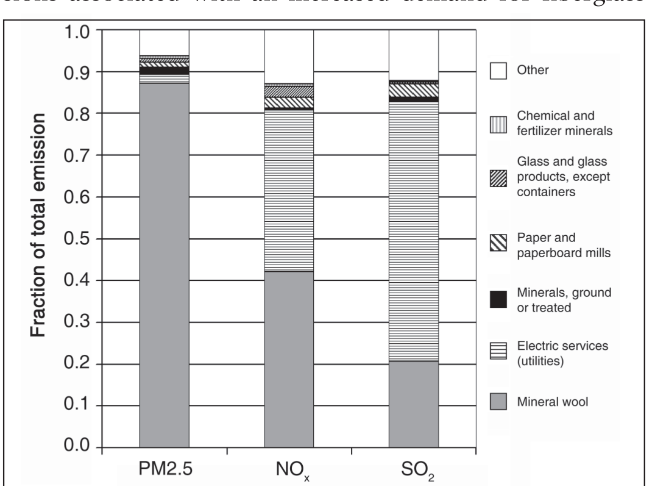


Fig. 3: Share of supply chain emissions by industry for fiberglass/mineral wool manufacturing

On the other hand, the total supply chain emission reductions associated with fuel source savings (direct plus indirect) are 20 tonnes of $PM_{2.5}$, 600 tonnes of NO_x and 800 tonnes of SO_2 per year. The upstream emissions correspond to 13, 23 and 5% of the total energy-related emission savings, respectively.

1.4 Exposure analysis

For our screening-level analysis, where no site-specific intake fractions were available, we applied the state-level regression-based intake fractions, assuming that plants are located at the centroid of each state and averaging results from ground-level source and power plant regression models. **Fig. 4** shows the intake fractions for primary $PM_{2.5}$ by state. The central estimates vary by an order of magnitude between Montana (1.4E-06) and Pennsylvania (1.4E-05), with higher values generally found in the Northeast. As expected, for both nitrates and sulfates (from NO_x and SO_2), the intake fractions vary less between the ground-level sources and power plants and across states (minimal difference related to stack height, factor of three range across states).

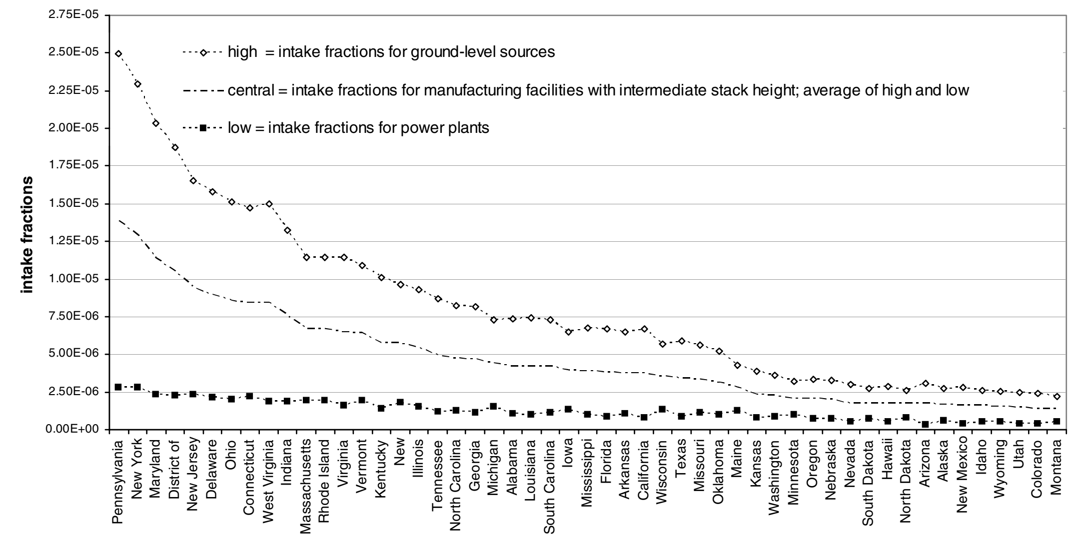


Fig. 4: Intake fractions for I-O analysis for screening-level calculations for manufacturing facilities (by state), assuming plant locations at state centroid

Applying these values, we calculate emission-weighted intake fractions by industry. **Fig. 5** shows an order of magnitude variability in the sector-specific intake fractions for primary $PM_{2.5}$. It should be noted that the primary $PM_{2.5}$ intake fractions for mineral wool manufacturing are higher than those for power plants or other fuel processes, related to the geographic location of plants. A complete list of intake fractions for all 490 BEA industries is available from the authors upon request.

Selected intake fraction values were refined based on the screening analysis findings, which demonstrated that most of the health impacts from insulation manufacturing were associated with direct primary $PM_{2.5}$ emissions. We applied ISCST3 to 7 plants that account for more than half of the total insulation manufacturing $PM_{2.5}$ emissions. The initial and updated intake fractions for the 7 plants are plotted in **Fig. 6**. The updated intake fraction estimates were similar to the 'first guess' central estimates (less than 30% difference at all sites),

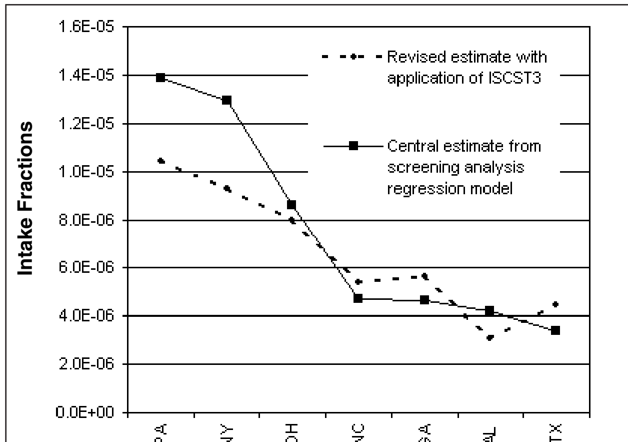
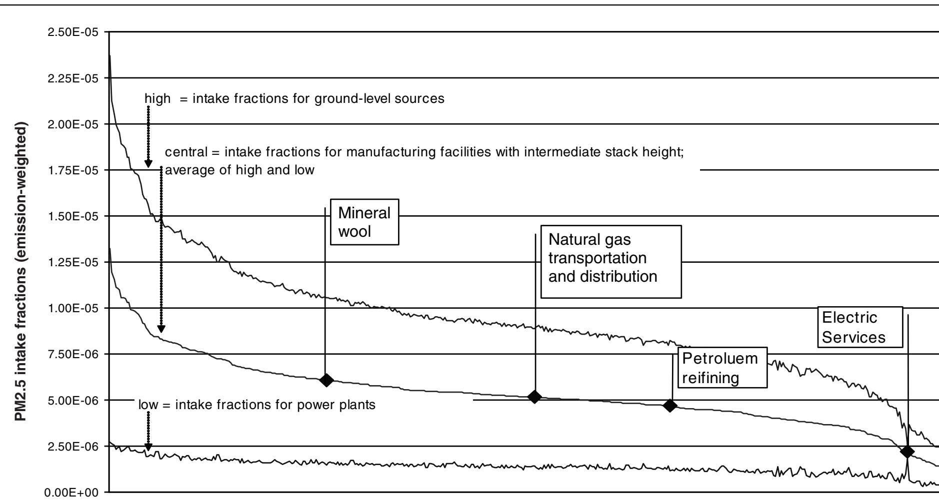


Fig. 6: Regression-based and directly modeled primary $PM_{2.5}$ intake fractions for high-emitting insulation manufacturers



Note: The estimates for 'electric services' are taken directly from a study from Wolff [15]; the lower and upper bounds represent 95% confidence interval (i.e. mean + 2 standard deviations).

Fig. 5: Distribution of emission-weighted intake fractions by BEA sector for primary $PM_{2.5}$

indicating the reasonableness of our estimates. Replacing the 'first guess' central estimates for those seven states with our refined estimates changes the total risk by only 1%.

1.5 Direct + upstream health effects

As depicted in **Fig.** 7, 83% of the total criteria pollutant health impacts from increased insulation manufacturing are attributable to the supply chain emissions from the mineral wool industry, of which 98% are associated with the direct primary $PM_{2.5}$ emissions from the industry. Note that the total economic output attributable to the mineral wool industry was only 54%. The disparity between the economic share and the impact share of the industry comes from the combination of emission intensities per unit of economic output as well as the plant locations, which affect both the dispersion patterns and exposure levels. The second highest contributor is electric services (8%), of which 78% is attributable to power bought directly by the mineral wool industry. In terms of mortality and morbidity, the central estimate of impacts from the supply chain is approximately 20 premature deaths, 500 asthma attacks, and 8,000 restricted activity days nationwide for one year of increased output.

For reduced end-use energy consumption, direct plus upstream criteria pollutant public health impacts avoided are 1.2 premature deaths, 30 asthma attacks and 600 restricted activity days per year, of which 0.1, 4, and 50 are associated with upstream emissions, respectively. This indicates the relative importance of direct emissions from power plants and residential fuel combustion.

In contrast, the cancer risks associated with the supply chain TRI emissions of mineral wool and fuel sources are both negligible. For the mineral wool supply chain, the total population cancer risk associated with air toxics emissions from one year of incremental insulation manufacturing is 1E-03. For the fuel source supply chain, the total cancer risk reduction from reduced energy consumption is 3E-5. Although the latter figure does not include end-use air toxic emissions, these calculations demonstrate that air toxic impacts will not influence total risk calculations, given the magnitude of the particulate matter impacts, and we omit them from further consideration.

1.6 Energy, emission and public health payback periods

The energy, environmental and economic impacts from the one-time manufacturing of insulation are recouped over years by impacts averted from the end-use energy savings. A payback period for a single-year cohort of new homes is helpful to evaluate the number of years it takes for the initial impacts to be recouped for a specific home or cohort of homes. On the other hand, code changes would lead to long-term changes in both insulation manufacturing and energy consumption, with both costs and benefits accumulating as new homes are built each year. Therefore, we calculate payback years for both a single-year cohort and multi-year cumulative cohorts.

The ATHENA building LCA database reports 30 MJ/kg as the embodied energy of fiberglass [13]. In our previous study, we found that the end-use energy savings was 5 quadrillion joules per year. The total mass of insulation required for the entire new housing market is 330,000 metric tons per year. Therefore, the embodied energy of fiberglass demanded each year to meet the energy standard would be 10 quadrillion joules, making the payback period for a single cohort of 1.2 million homes about 2 years. Alternatively, assuming that 1.2 million new homes are built every year with no changes in house size or type, the cumulative energy savings of the multi-year cohorts exceeds the total cumulative embodied energy in a little more than 2 years. In other words, a step change in state energy codes from current practice to IECC 2000 code requirements would yield net energy savings in approximately 2 years.

The emissions avoided by the direct plus upstream energy savings are 20 tonnes of $PM_{2.5}$, 600 tonnes of NO_x, and 800 tonnes of SO_2 per year. On the other hand, emissions added from mineral wool supply chains are 480 tonnes of $PM_{2.5}$, 1200 tonnes of NO_x and 1500 tonnes of SO_2. Therefore, the payback period for a single cohort of 1.2 million homes is a little less than 30 years for primary $PM_{2.5}$ and about two years for both NO_x and SO_2. For the cumulative multi-year cohorts, the payback period is approximately 50 years for primary $PM_{2.5}$ and two to three years for both NO_x and SO_2.

The public health benefits associated with direct plus upstream energy savings include 1.2 fewer premature deaths

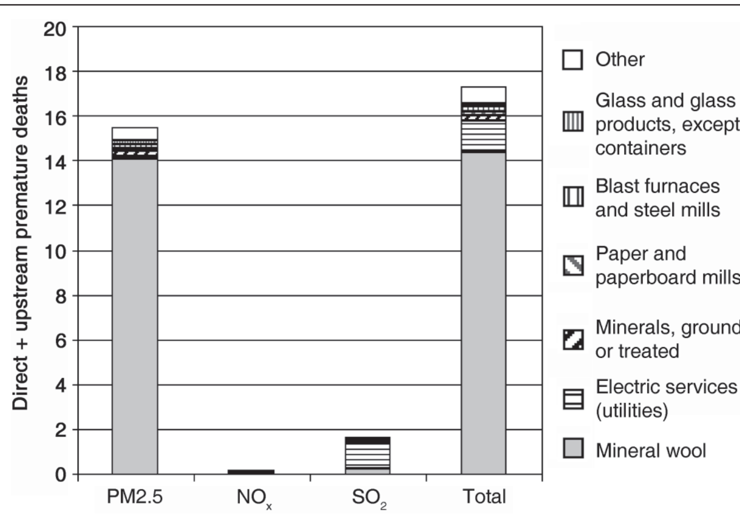


Fig. 7: Supply chain health impacts associated with incremental demand for fiberglass/mineral wool

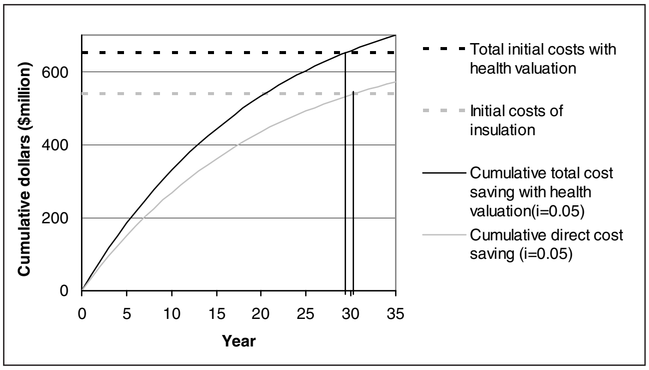


Fig. 8: Costs vs. benefits of insulation for single-year cohort, with and without health valuation (discount rate = 0.05)

per year. The best estimate of the number of premature deaths associated with the insulation supply chain is 17. Therefore, for a single-year cohort, it takes about 14 years for the cumulative health benefits to exceed the health effects associated with the initial insulation manufacturing. For the cumulative multi-year cohorts, the payback period for public health impacts is about 30 years.

Finally, the direct cost of additional insulation is $540 million for the homeowners, with direct cost savings from end-use energy reductions of $30 million per year. Therefore, assuming a 5% real discount rate, the payback period for the initial investment is almost 30 years for a single-year cohort (**Fig. 8**). With a 3% discount rate, the payback period is approximately 20 years. Conservatively assuming a 50-year lifetime for a new home, the net present value of increased insulation in a single cohort of new homes is $100 million with a 5% discount rate ($400 million with a 3% discount rate), indicating positive net economic benefits. Looking at the cumulative cohort, the net present value over 50 years is $500 million with a 5% discount rate ($4 billion with a 3% discount rate).

By monetizing health effects, we can compare the general magnitudes of individual expenditures and public health costs. Using the central estimates of valuation for mortality, asthma attacks and RAD, the total health cost from the insulation supply chain emissions is about $100 million. The annual health benefit from end-use energy savings is $8 million. Adding public health impacts to the economic calculation would reduce the payback period slightly, an indication that the energy sector is more emission/exposure intensive than the mineral manufacturing sector.

2 Discussion

We have demonstrated that with our risk-based approach it is feasible to incorporate regional variability in emissions and exposure into an input-output LCA. Our model enables a comprehensive health impact analysis using publicly available data and models, and provides a template for future risk-based I-O analyses. Although each LCA application will differ somewhat, it is likely that many of the lessons learned in our analysis are broadly applicable. For example, for relatively emissions-intensive processes, the tier 0 emissions may dominate the upstream emissions, even with a comprehensive input-output framework. Furthermore, if those emissions come from a few large identifiable sources, site-specific modeling within the LCA will then enhance the analysis. Broadly speaking, applying a screening analysis followed by selected site-specific modeling will be useful in most circumstances. Because the intake fractions display sufficient spatial variability, especially for primary pollutants, these site-specific dispersion models may improve the accuracy of the analysis considerably. Finally, for energy-intensive processes, it appears unlikely that air toxic cancer risks will contribute significantly to aggregate health benefit calculations.

For this case study, our calculations show that an analysis of direct economic costs and benefits has a similar payback period to an analysis that incorporates environmental externalities. This is because the emission/exposure intensity of end-use energy sources such as electricity, natural gas and fuel oil is about the same as the emission/exposure intensity for fiberglass/mineral wool production. The high emissions intensity of electricity for SO_2 and NO_x are offset by the high emissions intensity of mineral wool manufacturing for $PM_{2.5}$, when considered from a health risk perspective. In addition, the energy payback period for fiberglass/mineral wool manufacturing is significantly shorter than the direct cost payback period. This is partly because the energy intensity (energy consumption per dollar worth of fiberglass/mineral wool production) is lower than that of end-use energy sources. However, the embodied energy of 30 MJ/kg for fiberglass manufacturing may be underestimated due to the nature of process-based LCA data (i.e. system boundary issues). Yet, in all cases, the payback period is significantly shorter than the anticipated lifetime of new homes, indicating positive net societal benefits across all dimensions.

Further insight about the payback periods can be gained by comparing our results with those from the study by Hohmeyer and Brauer [14], described in the first half of our paper. The payback periods for NO_x and SO_2 are about 5 years or less in both studies. However, the payback period for primary $PM_{2.5}$ in our study is much longer (almost 30 years) than the 4 year payback period for total suspended particles (TSP) in Hohmeyer and Brauer. The rationale for this difference should be explored further, but could be related to differences in emissions profiles between Germany and the US or to the particle sizes considered in the two studies.

One of the difficulties in an analysis of this sort is determining whether the risk estimates are plausible, since observational data are not available. To provide a reality check for our calculations, we make a back-of-the-envelope comparison of our estimate of primary $PM_{2.5}$-related premature deaths from insulation manufacturing with a number that can be derived from a study of US power plant emissions [15]. In this study, the annual premature deaths associated with nitrates and sulfates that originate from power plants were approximately 30,000 for year 2007 emissions (approximately 2 million tons of NO_x and 9 million tons of SO_2). Most of the impacts were associated with sulfates, so we can estimate roughly 3,000 deaths per year per million tons of SO_2. In Wolff [16], the US average power plant intake fraction was an order of magnitude higher for $PM_{2.5}$ (2.2E-6) than for sulfate (2.2E-7). Thus, this estimate would correspond

to about 30,000 deaths per year per million tons of $PM_{2.5}$, or 0.03 deaths per year per ton of $PM_{2.5}$. Given incremental $PM_{2.5}$ emissions from the mineral wool manufacturing sector of roughly 500 tons per year and assuming proportionality, we would estimate about 15 (0.03 x 500) deaths from mineral wool manufacturing. This corresponds well with 16 premature deaths (related to $PM_{2.5}$) from our supply chain analysis, indicating that our estimate is plausible.

We have so far presented only the central estimates of the results from our I-O/risk analysis. However, this analysis involves a number of sources of uncertainty throughout, from input-output analysis, emission, exposure and risk calculations to valuation. Although a formal uncertainty analysis is not within the scope of our current study, it is important to evaluate uncertainty so that future studies focus on the appropriate parameters for improvement.

Lenzen lists six categories of uncertainties in I-O analysis [17]. The sources of uncertainty for I-O analysis include: (1) reporting errors in the economic transactions; (2) assumptions that factor inputs to domestic industries are identical for foreign industries; (3) assumption of homogeneity of foreign industries; (4) assumption of linearity between monetary and physical flow; (5) aggregation of different producers into one industry; and (6) aggregation of different commodities produced by each industry. Of these, the uncertainty associated with reporting and aggregation errors can be considered smaller than the proportionality and homogeneity assumptions, since the US I-O data are fairly complete and reasonably disaggregated into various sectors and commodities (478 commodities and 490 sectors). Also, it should be noted that, because I-O analysis involves numerous additions of coefficients, the relative standard errors of I-O data cancel out due to their stochastic nature [17]. Adapting hybrid approaches [18–21] where process-specific information for the core processes are incorporated with input-output information can improve the inventory analysis by reducing the uncertainty associated with the proportionality and homogeneity assumptions.

For the emissions calculations, there is uncertainty within the input emissions data due to estimation or reporting errors. We have relied on US EPA's AIRS database for the criteria pollutant emissions; however, the emission values for many sources are estimated by EPA and, therefore, are most likely different from the actual emissions. There also may be reporting or data entry errors. As an extreme example, we found a large error in the PM_{10} and $PM_{2.5}$ emission data for a mineral wool plant, which was overestimated by a factor of more than 80 (the application of which would have increased the sectoral emissions by more than a factor of 5). Also, we have assumed static conditions for emissions. In reality, however, emissions vary as a function of time with control technology, production levels, and regulations. For example, Maximum Available Control Technology (MACT) standards have been phased in for the mineral wool industry starting in 1999, which should clearly affect future PM emissions. Similarly, as Acid Rain Trading Program or NO_x SIP Call provisions or multi-pollutant power plant regulations come on line, emissions per unit energy from electric utilities will decline. Emission factors should be revised as new data become available.

The potential sources of uncertainty in risk calculations are building energy simulation, air emissions estimation, dispersion modeling, exposure estimation, and concentration-response functions. For these sources of uncertainty, we refer to our previous analysis [7] in which we conducted a formal uncertainty analysis of our risk-based model. The uncertainty importance analysis results for residential combustion showed that the most influential uncertainty was the uncertainty in the concentration-response function for premature mortality, regardless of pollutant or region. Second in importance in most cases was the total uncertainty in estimates of avoided exposures (i.e. the intake fractions applied), followed by more minor uncertainties due to issues regarding affected population and background rates of disease. Since our current risk analysis framework is built upon our previous analysis, we can infer that the same factors are likely to be important for the current analysis as well.

For the concentration-response function, we used a 0.5% increase in premature deaths per unit increase ($\mu g/m^3$) in $PM_{2.5}$ concentrations, as derived from the ACS cohort study [22]. Alternatively, a concentration-response function can be derived from time-series analyses with an assumption that increases in particulate matter concentration only cause acute mortality and not chronic mortality. An extreme hypothesis could be that people whose deaths are attributed to air pollution were in poor health and that the loss of life expectancy was less than a year. Applying a concentration-response function derived from time-series studies (an approximate 0.1% increase in mortality per $\mu g/m^3$ increase in $PM_{2.5}$) [23–25] and US EPA's value of statistical life year ($360,000) for one year [26], the value of total health effects from both the insulation manufacturing supply chain and the end-use energy savings decrease by 97%. Therefore, a better understanding of concentration-response relationships, the number of life-years lost, and economic values for premature mortality would greatly improve the final health valuation estimates. However, it should be noted that the changes are proportional across all source categories, with no effect on the public health payback period.

Another source of uncertainty in concentration-response functions is the relative toxicity of different forms of particulate matter. In our study, we assumed identical toxicity for all $PM_{2.5}$ constituents regardless of emission sources. Some epidemiological studies report fewer health effects associated with non-combustion-related particulate matter than combustion-related PM [27,28], and the relative toxicity of sulfates, nitrates, and various forms of primary PM may differ. Therefore, relative particle toxicity could change our results substantially, especially if the particulate matter emissions from insulation manufacturing were non-combustion-related and the emissions from energy sources were combustion-related. To resolve this issue, further study is warranted both on relative particle toxicity and on the composition of emissions from insulation manufacturing.

Finally, it should be noted that our public health cost calculation captures only an unknown portion of total societal costs even from the environmental health perspective alone. In conventional LCIA, a total societal cost-benefit analysis would include not only health effects, but also costs of global warming, acidification, ozone depletion, and so forth. Therefore, the

true societal costs and benefits of increased insulation could be higher than what we have presented in this paper.

In spite of the uncertainties in our analysis, our study can help decision-makers evaluate the costs and benefits of policy options from a combined public health and life cycle perspective. Even conservatively assuming 50 years for the lifetime of an average US home, the comparison of the energy savings benefits and supply chain costs indicates that the payback period for energy, cost, emissions and health effects all result in positive net benefits over the lifetime of the home. Our approach can apply to other energy efficiency measures so that decision-makers can select the strategies for energy policy that return the highest societal benefits given limited resources. In terms of methodology, the location-weighted intake fractions can overcome the difficulty in incorporation of regional exposure in LCIA. Our two-stage analysis for exposure estimation, first using regression-based intake fractions followed by more refined dispersion modeling, ensures that stack height effects and exposure concepts are well incorporated into the analysis. The refinement step is recommended especially if primary $PM_{2.5}$ is an important source of exposure and if stack heights are relatively low (although it should be noted that the refined intake fractions had a relatively small effect on the results in this case study). On the other hand, where secondary $PM_{2.5}$ is more important, use of regression-based intake fractions would be sufficient for a reasonable risk approximation.

3 Conclusion

We have developed and applied a risk-based model to quantify the public health costs and benefits of increased insulation in new single-family homes in the US. Our approach allows for the interpretation of emissions inventories from both end-use energy savings and upstream manufacturing and energy processes, taking into account economy-wide emissions and the regional variability in both emissions and exposure. Assuming a 5% discount rate, the net present value of economic benefits over a 50-year period for a single-year cohort of new homes is $100 million, with 40 fewer premature deaths in this period (with cumulative benefits of $500 million and 700 fewer premature deaths). While uncertainties in our model need to be considered carefully in the actual decision-making processes, our analytical framework allows for integration of risk analysis tools into life cycle assessment for any analysis of energy efficiency policy.

Acknowledgments. This research was supported by the North American Insulation Manufacturers Association.

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Received: January 10th, 2002
Accepted: December 14th, 2004
(due to illness of the corresponding author)
OnlineFirst: December 14th, 2004